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Weather Prediction[1]

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Introduction

Today's large electronic computers are absolutely essential to modern weather forecasting. Not only did the era of modern weather forecasting open with the invention of the stored-program electronic computer, but the subsequent developments of public weather forecast services were paced by advances in computer technology and continue to be.

On June 10, 1952, the Institute for Advanced Study in Princeton, N.J., announced the successful development of the first stored-program electronic computer. John Louis von Neumann had designed the logic of the system, whose fundamentals are still to be found in today's large computers. Three years after the public announcement of von Neumann's computer, the U.S. Government acquired one of the first commercial stored-program electronic computers, an IBM 701, and by the summer of 1955 was producing numerical weather predictions on an operational twice-daily schedule. Rapid development of this new scientific discipline followed. It remains a field of rapid advances, and has revolutionized the public weather forecast services.

The Institute Electronic Computing Project was organized beginning in 1946 at the Institute for Advanced Study, under von Neumann's direction. Its mission was to develop and build the new computer that was announced six years later. As part of the Project, the Meteorology Group was organized in 1948. The goal of the Group was to develop and demonstrate the feasibility of numerical weather prediction, that is, weather forecasting by numerically integrating the classical equations of hydrodynamics and thermodynamics. Weather forecasting was one of a very few scientific areas chosen by von Neumann for intensive application of the first modern computer. In his history of computers, Goldstine (1972, p. 300) opens a chapter on applications to meteorology, "As we mentioned earlier, the aim of the Institute Electronic Computer Project was a threefold thrust into numerical mathematics, some important and large-scale application, and engineering. For the second effort von Neumann chose numerical meteorology." Jule G. Charney led the Meteorology Group throughout its highly productive eight-year life. Although the Group first succeeded in integrating the equations on the ENIAC, an automatic computer that was a predecessor of stored-program machinery, it was on von Neumann's machine that they proved the operational feasibility of Numerical Weather Prediction. Whereas a 24-hour forecast took about 24 hours to calculate on the ENIAC, it took only about 5 minutes on von Neumann's machine!

The executives who set priorities and make decisions to provide the required personnel, equipment, and funds seldom receive a fair share of the credit for scientific and technical breakthroughs. The creative scientists by right should receive a major share, but also should the executives who often take the initiative in seeking out people with new and more promising approaches to problems, and with limited resources make correct and timely decisions. The prompt reaction of the government weather services to the momentous event of the opening of the computer age and the development of numerical weather prediction was due to the foresight of a small committee of government officials and their advisers. The Joint Meteorology Committee was composed of Dr. Francis W. Reichelderfer, Chief of the U.S. Weather Bureau; Brig. Gen. Thomas S. Moorman, Commanding General of Air Weather Services, U.S. Air Forces; and Captain Robert O. Minter, Commander of the Naval Weather Service, U. S. Navy. The principal advisers were Dr. Harry Wexler of the Weather Bureau and Dr. George P. Cressman of the Air Weather Service. They agreed among themselves that each of the three weather services would provide a third of the personnel and funds required to mount a national effort in operational numerical weather prediction.

The initial organizational problems were solved by the three weather services establishing the Joint Numerical Weather Prediction Unit in the Weather Bureau, but responsive to the Joint Meteorology Committee. The Unit subsequently developed operational prediction models, developed numerical methods of analysis of initial weather conditions, and began the development of automatic weather communications, data plotting, and graphics. Like the Meteorology Group at the Institute for Advanced Study, the Joint Numerical Weather Prediction Unit had a relatively short life, but it had three direct descendents. The divergent requirements of the three weather services led in 1961 to the dissolution of the Unit, and the establishment of the National Meteorological Center (National Weather Service), the Global Weather Central (U.S. Air Force), and the Fleet Numerical Weather Central (U.S. Navy). The National Weather Service, by the way, is the new name of the old U.S. Weather Bureau. It is to the credit of succeeding heads of weather services and other decision-makers in government that the three centers thrived and continue to do so. Indeed, numerical weather prediction is the centerpiece of developing and improving weather services, as well as modern meteorology generally.

All of the meteorological world was watching the work of the Meteorology Group at the Institute for Advanced Study, and, especially in its early years, the Joint Numerical Weather Prediction Unit. Within a few years after the establishment and first successes of the Joint Numerical Weather Prediction Unit, many countries followed the lead of the United States, among them Sweden, Union of Soviet Socialist Republics, Federal Republic of Germany, United Kingdom, Norway, Canada, Australia, and France. Virtually all developed, and many lesser developed, nations now have computer-equipped weather centers.

Although the United States established the first operational weather computer center, and has continuously supported it to this day, it would be a mistake to think of it as a purely national effort. Far from it, for many essential ideas behind numerical weather prediction came from elsewhere. The outstanding example is Carl-Gustav Rossby, born and educated in Sweden, with his career alternating throughout his life between U.S. and Sweden and perhaps the greatest meteorologist of this century, whose basic work done from the 1930's onward formed the basis of early numerical weather prediction. Von Neumann tried to attract him to join the Institute Electronic Computer Project, but only succeeded in bringing him as a visitor during early 1951. As one of the great teachers of dynamic meteorology, however, Rossby's influence lived in his students, and many of the early workers in numerical weather prediction were young and had been students of his.

The Scientific Problem

The atmosphere is an approximately spherical thin gaseous shell about the earth, some 13,000 km in diameter, with 50% of its mass below $5\frac{1}{2}$ km above the surface, and 90% of its mass below 16 km. In the mean it is rotating with the earth, although in both Northern and Southern Hemispheres in middle latitudes so-called jet streams at about 10 km completely circle the poles as ever-present vast vortices. The jet streams are westerly and slowly undulate north and south in up to 5 or so very long waves. These waves of planetary scale strongly influence the development and motion of systems of smaller scale, and vice versa.

Numerical weather prediction at present deals principally with the prediction of large cyclonic storms and anticyclones, which are several hundred to several thousand kilometers across, somewhat smaller in scale than the planetary waves. Because of interactions among scales both this storm scale and the planetary scale must be explicitly predicted. Likewise the effects of even smaller scales must in some way be accounted for to gain maximum achievable forecast skill. This is done by including in the equations turbulence, diffusion, and friction terms and other supplementary numerical processes. In writing the equations below, I do not show these terms and processes explicitly, but indicate them with appropriate symbols.

Newton's second law of motion

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv + \frac{1}{\rho}\frac{\partial p}{\partial x} = F_x \qquad (1a)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu + \frac{1}{\rho}\frac{\partial p}{\partial y} = F_y \qquad (1b)$$

$$g + \frac{1}{\rho}\frac{\partial p}{\partial z} = 0 \qquad (1c)$$

First law of thermodynamics

$$c_v\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right)$$

$$+ p\left(\frac{\partial \rho^{-1}}{\partial t} + u\frac{\partial \rho^{-1}}{\partial x} + v\frac{\partial \rho^{-1}}{\partial y} + w\frac{\partial \rho^{-1}}{\partial z}\right) = H \qquad (1d)$$

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \qquad (1e)$$

Conservation of water vapor

$$\frac{\partial q}{\partial t} + u\frac{\partial q}{\partial x} + v\frac{\partial q}{\partial y} + w\frac{\partial q}{\partial z} = E \qquad (1f)$$

Equation of state for perfect gases

$$p\rho^{-1} = RT \qquad (1g)$$

where t is time and the known (time independent) variables are

x, y	horizontal cartesian coordinates
z	height above mean sea level
f	Coriolis parameter
g	acceleration of gravity
c_v	specific heat of air at constant volume
R	gas constant for air

and the unknown (time-dependent) variables are

u, v, w	x, y, z-components of velocity vector
ρ	density
p	pressure
T	temperature
q	specific humidity

F_x and F_y are accelerations due to friction, and drag of topography. H is heat added to the system by radiation, transfer from earth and oceans, and condensation and evaporation. E is evaporation (positive) into the atmosphere and condensation (negative) of water vapor. The Coriolis forces, fv and -fu are apparent forces due to earth's rotation. Equation (1c) states the hydrostatic condition, i.e., that pressure at a given point equals the weight of air above the point. On the storm scale and larger, the ratio of gravitational acceleration g to vertical accelera-terms that are neglected is about 10^7, so it is a very accurate approximation Note that these equations are in cartesian coordinates, and thus do not account for the spherical shape of the earth and atmosphere. In practice additional, so-called metrical, terms must be included, but they are not necessary for my purpose here, which is merely to illustrate the nature of the computations that need be done.

Now, these equations are for a continuous medium, but our computers are digital. They therefore can be integrated only by numerical estimate. Similarly, the derivatives in space cannot be evaluated except by estimations. In effect, then, we do not integrate these partial differential equations, but rather solve a set of albegraic so-called partial difference equations whose solution we think approximates the integrals. The most common way to approach the problem today is to approximate the derivatives in space and time with finite-difference ratios. I should mention, however, that there is a trend toward use of orthogonal functions, such as spherical harmonics, for estimating the partial derivatives in space.

In order to be concrete in illustrating the computations, and still keep the equations and discussion within reasonable bounds, I will here consider a simplified set. A descriptive consideration of the atmosphere, especially of its vertical structure, suggests a set of vertically integrated equations (Charney, 1949). The equations (1) are thus reduced to the shallow water equations. As written below, the terms containing the effects of very small scale, as well as heat and evaporation, are omitted.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fv + g\frac{\partial h}{\partial x} = 0 \qquad (2a)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fu + g\frac{\partial h}{\partial y} = 0 \qquad (2b)$$

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} + h\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0 \qquad (2c)$$

where u and v are the vertically mass-averaged horizontal velocity components, and h is a scalar whose gradient times g is the vertically mass-averaged pressure force. In practice, h is reduced by a factor of about 4, to bring the behavior of planetary waves into correspondence with those of the atmosphere. The wind components are interpreted as u and v on the 50 kPa isobaric surface, and h is interpreted as the height of that surface. The 50 kPa surface is roughly at the half-mass level; about half the mass of the atmosphere is above it, and about half below it. The set (2) of equations is referred to by meteorologists as the <u>barotropic</u> <u>model</u>. Considering their simplicity, they give a remarkably good prediction of the wind field at about 5 1/2 km, from which valuable inferences about surface weather can be made by experienced meteorologists. The first skillful numerical weather predictions were made during the 1950's with such a model.

In practice, u, v, and h are given initially on a regular square grid of points in x and y, and their subsequent values are predicted on the same array. Let Δ be the spacing between grid points, the same in each dimension, x and y. Let Δt be the time step used to approximate the partial derivatives in time. Let i, j, k be the serial numbers of points in the x, y, t-dimensions, respectively. That is, $x = i\Delta$, $y = j\Delta$, $t = k\Delta t$. For convenience and economy in writing I introduce a symbolism for finite-difference ratios:

$$u_{2t} = \frac{u_{i,j,k+1} - u_{i,j,k-1}}{2\Delta t} \cong \frac{\partial u}{\partial t} \qquad (3a)$$

$$u_{2x} = \frac{u_{i+1,j,k} - u_{i-1,j,k}}{2\Delta} \cong \frac{\partial u}{\partial x} \tag{3b}$$

$$u_{2y} = \frac{u_{i,j+1,k} - u_{i,j-1,k}}{2\Delta} \cong \frac{\partial u}{\partial y} \tag{3c}$$

and similarly for the dependent variables v and h. Replacing the derivatives in (2) with these approximations, we get

$$u_{2t} + uu_{2x} + vu_{2y} - fv + gh_{2x} = 0 \tag{4a}$$

$$v_{2t} + uv_{2x} + vv_{2y} + fu + gh_{2y} = 0 \tag{4b}$$

$$h_{2t} + uh_{2x} + vh_{2y} + h(u_{2x} + v_{2y}) \tag{4c}$$

We note that in the equations (4) with the symbols defined as in (3) all of the terms except the first can be evaluated with values of u, v, h at the current time step, k. We can therefore easily find u_{2t}, v_{2t}, h_{2t}, and knowing the values at time step k-1, we can find u, v, h at time step k+1. We then march forward in time, repeating the process until the desired forecast period is reached.

The approximations (3) are called <u>centered</u> differences, not involving values at i, j, k. Because of the centered differences in time, at the start of the prediction, fields of the dependent variables are required at two time steps (k=0 and k=1). Common practice is to input values for time step zero and generate the values for time step one by replacing u_{2t} with

$$\frac{u_{i,j,1} - u_{i,j,o}}{\Delta t}$$

and similarly for v and h. The steps in time cannot be repeated using such approximations, however, because the resulting computational system would be unstable, with exponential growth of energy. This can easily be shown by linear analysis.

Linear analysis also shows that Δt cannot be chosen arbitrarily, but must be related to Δ by

$$\Delta t < \Delta / c$$

otherwise exponential growth rates would be encountered in the solution. The quantity <u>c</u> is the magnitude of largest signal velocity, taken to be the sum of the wind speed and the speed of propagation of gravity waves, i.e.,

$$c = \sqrt{u^2 + v^2} + \sqrt{gn}$$

For our application $\sqrt{gh} \cong 140\ ms^{-1}$ and $\sqrt{u^2 + v^2} < 100\ ms^{-1}$, so that $c < 240\ ms^{-1}$.

In the early days, the barotropic model was regarded as a large calculation. The IBM-701 operated at about 0.02 MIPS (million instructions per second). With Δ = 300 km, it took about 4000 grid points to cover a polar stereographic map (true at 90N) of the Northern Hemisphere. The smallest grid interval, measured on earth rather than on the projection, was at the equator and was 150 km, and for stability Δt was taken as 10 min. There were thus 144 time steps in a 24-hr prediction, and about 144 x 4000 = 576,000 points in space-time at which equations (4) needed to be calculated. The number of instructions, including fetches and storage of intermediate results, was about 100 at each point in space-time when the additional metrical terms were added. Thus about 60,000,000 instructions were required for a 24-hr forecast, requiring 45-60 min of calculation on a 0.02 MIPS machine.

The process described is quite simple in concept, even when applied to the full set of equations (1). There are a number of difficult problems, however. To begin with, the equations (4) are given here as the simplest finite-difference approximations term by term to (2). As a matter of fact, these particular approximations do not yield a stable solution. I will not go into them here, but operations other than the difference operations shown must be applied to the variables to achieve stability. (Shuman, 1962 and 1974; Arakawa, 1966; Marchuk, 1967).

The barotropic model equations (2) themselves have two serious disadvantages. They cannot predict the transformation of potential energy stored in the atmosphere's thermal field into kinetic energy. Thus, the generation of storms is lost to them, although experienced forecasters could often infer storm formation because of its association with certain predicted features. Secondly, the barotropic model yields predictions at only one level in the atmosphere.

Present day operational models use the full set of equations (1), with the vertical coordinate resolved with information at 5-10 levels, and with $\Delta \cong 200$ km at 90N. With present operational machinery about 600 times faster than the old IBM-701, forecasts are run in about the same time now as the simpler models were then. We now run a number of models for various purposes, including a highly resolved model covering a small area ($\sim 9 \times 10^6\ km^2$), run on-call when hurricanes or flash floods threaten United States territory. I will describe, however, only the currently operational model that covers the Northern Hemisphere.

The basic framework and numerical system of the model have been described by Shuman and Hovermale (1968), although the horizontal grid interval is smaller (200 km at 90N) and the vertical resolution is somewhat different. Figure 1 shows the area of integration, together with a sample of the grid points in the lower left corner. Figure 2 shows the vertical resolution. The vertical coordinate used is not z, the height above mean sea level, but is chosen so that earth's surface (or a representation of it smoothed to be consistent with the model's horizontal resolution) is a coordinate surface. Since air does not pass through earth's surface, this lower boundary is also a material surface, i.e., air particles initially on the surface remain on it. There are two other material surfaces in the coordinate system. One is the tropopause, the boundary between the troposphere which is only moderately hydrostatically stable, and the stratosphere which has a high degree of hydrostatic stability. The tropopause over large areas is a very sharp discontinuity in the lapse rate of temperature with height, and is closely associated with maxima of wind speed in the vertical. In the real atmosphere it closely approximates a material surface for several days at a time. Passing a coordinate surface through it thus improves vertical resolution without the cost of increasing the number of levels. In any case the transformation of the coordinates is strictly mathematical, not explicitly taking into account the physical structure of the atmosphere. Thus the only explicitly physical implication is that the sheet of particles initially on the tropopause is a coordinate, history-carrying, surface throughout the numerical integration.

The third material surface is the top of the model, placed on a constant pressure surface of 5 kPa. The upper boundary condition there is that the pressure remains 5 kPa, and of course, that air does not pass through the 5 kPa isobaric surface. This condition avoids certain difficulties with the atmosphere's true upper boundary condition, that no air leaves or enters the atmosphere. The difficulties arise from the fact that the upper boundary of the atmosphere is at infinite height. Although not strictly true, the upper boundary condition of the model has a physical analogue in a limiting sense. The analogue is the replacement of the atmosphere above the 5 kPa surface with a fluid in hydrostatic balance of vanishingly small density. Only about 5% of the atmosphere's mass is above 5 kPa, by the way.

I should say something about other problems connected with numerical weather prediction. On the scales that it presently deals with, there is a rather simple approximate relation between the wind and pressure fields. The leading terms in the equations of motion (1a) and (1b) tend actually to be smaller than the coriolis and pressure force. Thus,

$$v \cong \frac{1}{f\rho}\frac{\partial p}{\partial x}$$

$$u \cong -\frac{1}{f\rho}\frac{\partial p}{\partial y}$$

The vector thus defined is called the <u>geostrophic</u> wind. For initial conditions, independent analyses of wind and pressure fields not only must be quasi-geostrophically related, but also should exhibit a rather delicate, even subtle, balance with each other. Otherwise, large spurious oscillations of a gravitational nature would occur in the solution, and even more serious errors might result. The subtle balances involved can only be expressed in terms of solutions of differential equations. The balances are sufficiently subtle that errors in the observations mask them. This whole problem is called the initialization problem and is not fully solved yet.

Particularly in the tropical regions and in summer in the temperate zones, small scale vertical overturning results in mixing of momentum, heat, and moisture, which modifies the vertical structure of the atmosphere over large areas. The individual cells are far too small to be carried explicitly in the net of grid points, and their mechanics are at least as complicated as the large-scale systems. To account for their effect on the large-scale systems, they are parameterized. That is to say, attempts are made to relate them to the larger scale fields of variables that are explicitly carried. (Kuo, 1974; Arakawa and Schubert, 1974).

Radiation effects are also important, both the short-wave radiation received from the sun, and the long-wave radiation emitted by earth and atmosphere. Although rather complete versions of the radiation equation have been incorporated and run in research models (Manabe and Strickler, 1964; Fels and Schwarzkopf, 1975), the calculations are far too many for an operational model, which must meet rather strict deadlines for completion. Simpler versions of the radiation equation must suffice for operational models. Radiation effects should account for the high albedo of clouds and snow and ice cover as well as the more constant variations of albedo over continents and oceans. It is a tricky business to design an abbreviated version of the radiation calculations in order to get as much benefit as possible with as little calculation as possible.

It is important to handle the moisture cycle accurately, especially condensation for predicting cloudiness, and the accumulation of rainfall, snowfall, etc. Indeed, from the standpoint of the public, the latter <u>is</u> the weather they are most interested in most of the time. In many cases, the moisture that precipitates is already in the atmosphere as the forecast procedures begin. In some cases, however, the moisture that is forecast to precipitate evaporates from oceans during the forecast period. These cases, though perhaps infrequent, can be very important. For example, the 50-year record snowfall on the Atlantic seaboard February 18-19, 1979, was water picked up from the mid-latitude Atlantic by Arctic, originally dry, air.

When cold air passes over warm water, heat is also transferred to the atmosphere by conduction and convection. The processes involved depend on a scale of events in the vertical far too small to be described perfectly with today's models. Like the other things I have been talking about here, we are computer limited here also.

Impact on National Weather Forecast Services

Numerical weather predictions issued from the National Meteorological Center, near Washington, D. C., with some exceptions, are not issued to the using public, but are used by field forecasters as guidance in serving the public. The guidance package issued to forecasters includes not only numerical weather predictions, but also some subjectively modified charts and automated statistical interpretations and enhancements of numerical weather predictions. The latter include diurnal maximum and minimum temperatures and probabilities of rain, snow, thunderstorms, etc. Thus, numerical weather prediction is only a part of the total forecast service, albeit an essential part. For a brief summary of the national forecast services, the reader is referred to Shuman (1978).

The primary output of the National Meteorological Center is graphical, and the sheer bulk is staggering by yesteryear's standards. Some 500 charts per day are transmitted on facsimile networks. Over 85% of these charts are fully automated; the rest are manual modifications of automated products. Figure 3 is an example of the automated charts. It is the 48-hr numerical weather prediction of pressure at mean sea level (solid lines) that was issued for the record-breaking New England winter storm of February 1978. It was an excellent forecast, as shown by Figure 4. Brown and Olson (1978) describe in detail the forecast performance for this storm. Ten years ago, a prediction of this excellence could not have been made.

Figures 5 and 6 illustrate how both central guidance and public forecasts have improved during the quarter century of operational numerical weather prediction. Figure 5 is a graph of annual averages of a skill score based on Tewles' and Wobus' (1954) so-called S_1 score. The skill is that of the forecast geostrophic wind pattern at 50 kPa, a good indicator of the skill of the wind pattern at all levels. By this measure the skill of the central guidance has doubled since the days before numerical weather prediction.

Figure 6 is a simple measure of error in forecasts of temperature issued to the public. The longer record is for Salt Lake City only, because it is the only station with such a long record. The shorter record is for the area local to all Weather Service Forecast Offices from which records are available. The statistic shown is the annual number of forecasts that were wrong by more than 10°F (5.6°C).

In summary, the numerical weather predictions prepared on the fastest computers commerically available have become essential to the national forecast service during the past 25 years. Improvements in numerical weather prediction, paced by advances in computer technology, have led to substantial, sometimes dramatic, improvements in the skill of forecasts issued to the public. It is fair to say that future progress in weather forecasting depends on more accurate numerical weather predictions, which in turn depend on more powerful computers.

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LEGENDS

Figure 1. Polar stereographic map showing area of integration of the currently operational hemispheric model of the National Meteorological Center. The midpoints of the sides of the area are at 1.4°S latitude, the corners at 20.8°S. A sample of the grid is in the lower left corner.

Figure 2. Schematic of the vertical resolution of the currently operational hemispheric model of the National Meteorological Center. Vertical velocity, pressure, and height are carried at the eight levels shown; Horizontal velocity components and temperature, in the seven layers between the levels. The levels shown are coordinate surfaces. The vertical coordinate is based on pressure. The boundary layer is precisely 10 kPa thick; the troposphere and stratosphere are each divided into three equal pressure intervals. On the left side, rough approximations of the pressure are given for the various levels. The top level, however, is at precisely 5 kPa, about 20.6 km high.

Figure 3. A 48-hr forecast that was issued for the record-breaking New England blizzard of 1978. A crippling twenty-seven inches of snow fell on Boston during this storm, accompanied by hurricane force winds with gusts peaking at 83 mph. The solid lines are isobars of pressure at mean sea level, labeled in hPa (millibars) with only the units and tens digits showing. The pressure at the low center is 990 hPa (99 kPa). The broken lines are isohyets of thickness between the 50 and 100 kPa surfaces, labeled in white on black boxes in dekameters. The 50-100 kPa thickness is proportional to the mean temperature below 50 kPa (about 5½ km). In areas of precipitation the 554 dam line generally separates rain and snow areas.

Figure 4. The observed pattern of pressure at mean sea level, corresponding to the 48-hr forecast shown in Figure 3. Labels are in hPa (with all digits shown).

Figure 5. Record of skill, averaged annually, of the NMC 36 h, 50 kPa (~ 5.6 km high) circulation predictions over North America. The horizontal bars show averages for the years during which no major changes in models occurred. Years of transition are not included in the averages. The Geostrophic Model (Cressman, 1963) is a generalization of the Barotropic Model, to account for baroclinic effects. The last bar shows the effect on skill of a change in input wind. Prior to 1972 a quasi-geostrophic wind field, derived from the pressure field, was used for initial winds. During 1972, analyses of observed winds were used instead. The measure of skill is based on the so-called S_1 score (Teweles and Wobus, 1954), which is a measure of normalized error in horizontal pressure gradients. A chart with an S_1 score of 20 is virtually perfect, and one with 70 is worthless. As shown, skill (percent) is $2 \times (70-S_1)$, which yields 0 for a worthless chart, and 100 for a virtually perfect one. The last point, for 1978, is an all-time annual record, but will probably be sustained in future years. The model with the new higher resolution described in this article was implemented on January 19, 1978, and the record score is ascribed to the change in resolution.

Figure 6. Forecast temperature errors greater than 10°F. Salt Lake City is the only station that has kept a consistent record of this for over 20 years, and its record is shown to illustrate improvements over a longer period. The shorter record is for forecasts local to WSFO's, which are scattered fairly uniformly about the country, and is the average number per WSFO. Both curves are for forecasts 36-48 hr in advance. The Salt Lake City record is for one forecast per day (365 each year). The shorter record is for two forecasts per day, but only for the colder half of the year, Oct. 1 to Mar. 31. The difference in level of the two curves is largely due to two factors. 1) It is more difficult to forecast temperature in the colder seasons because temperature variations are larger. 2) The variation of temperature over the Great Basin is smaller than elsewhere, for example, over the Great Plains. To remove large fluctuations that appear year-to-year in single-station records, data for Salt Lake City have been smoothed with weighting factors 1:2:4:2:1.

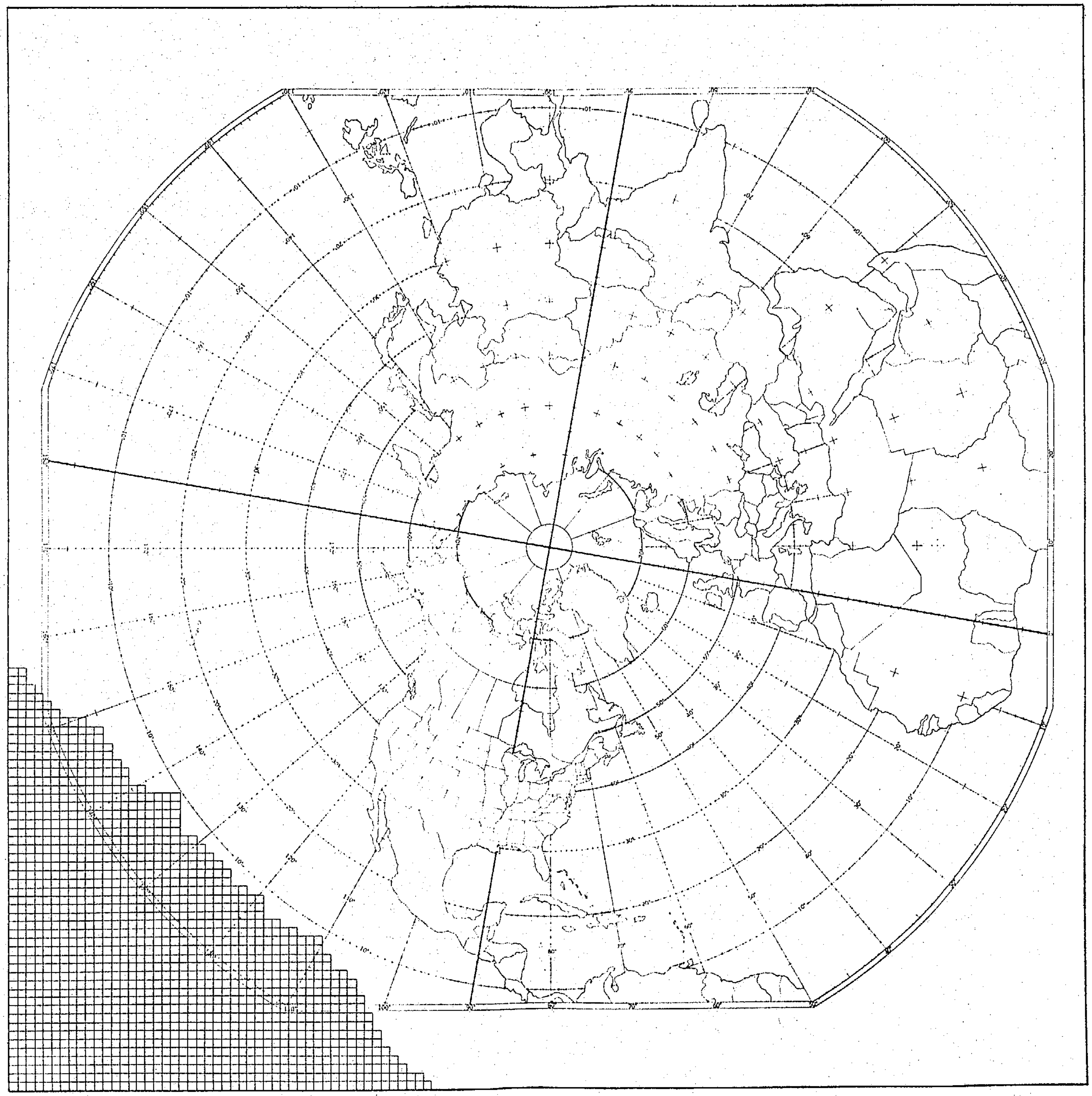


Fig. 1

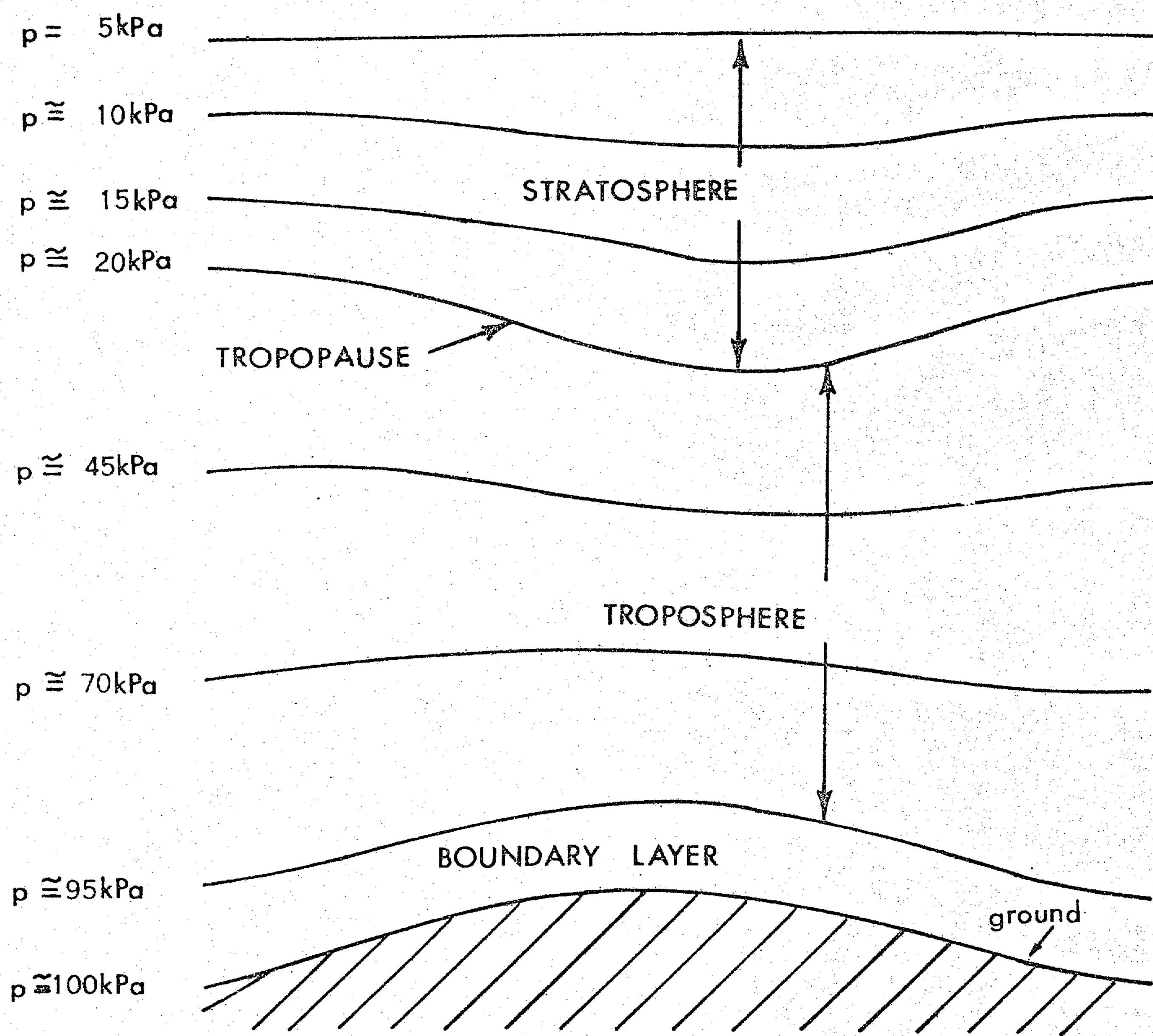

p = 5kPa
p ≅ 10kPa
p ≅ 15kPa
p ≅ 20kPa
STRATOSPHERE
TROPOPAUSE
p ≅ 45kPa
TROPOSPHERE
p ≅ 70kPa
BOUNDARY LAYER
p ≅95kPa
ground
p ≅100kPa

Fig. 2

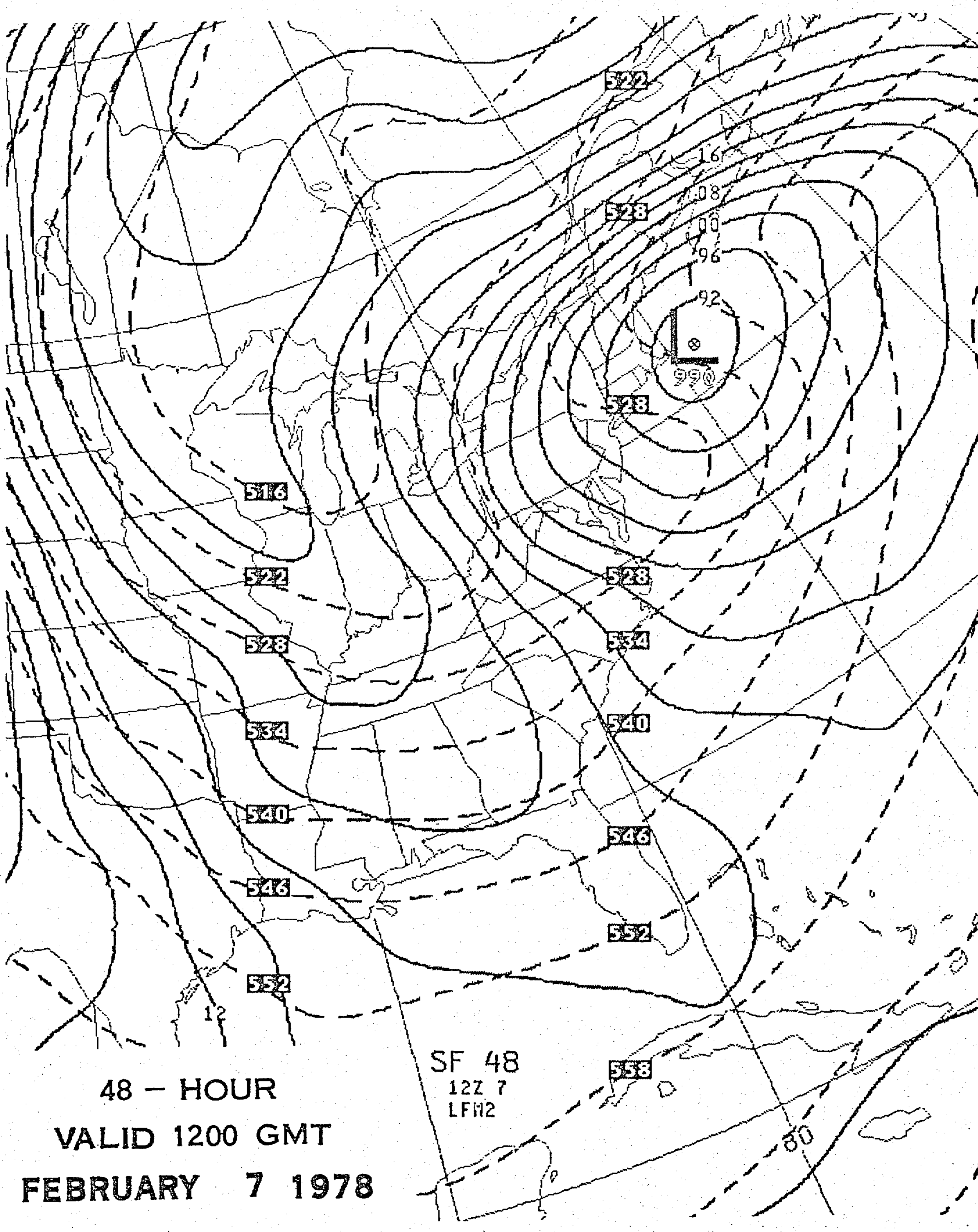

522
16
08
528
00
96
92
990
528
516
522
528
528
534
534
540
540
546
546
552
552
12
558
SF 48
12Z 7
LFM2
80
48 – HOUR
VALID 1200 GMT
FEBRUARY 7 1978

Fig. 3

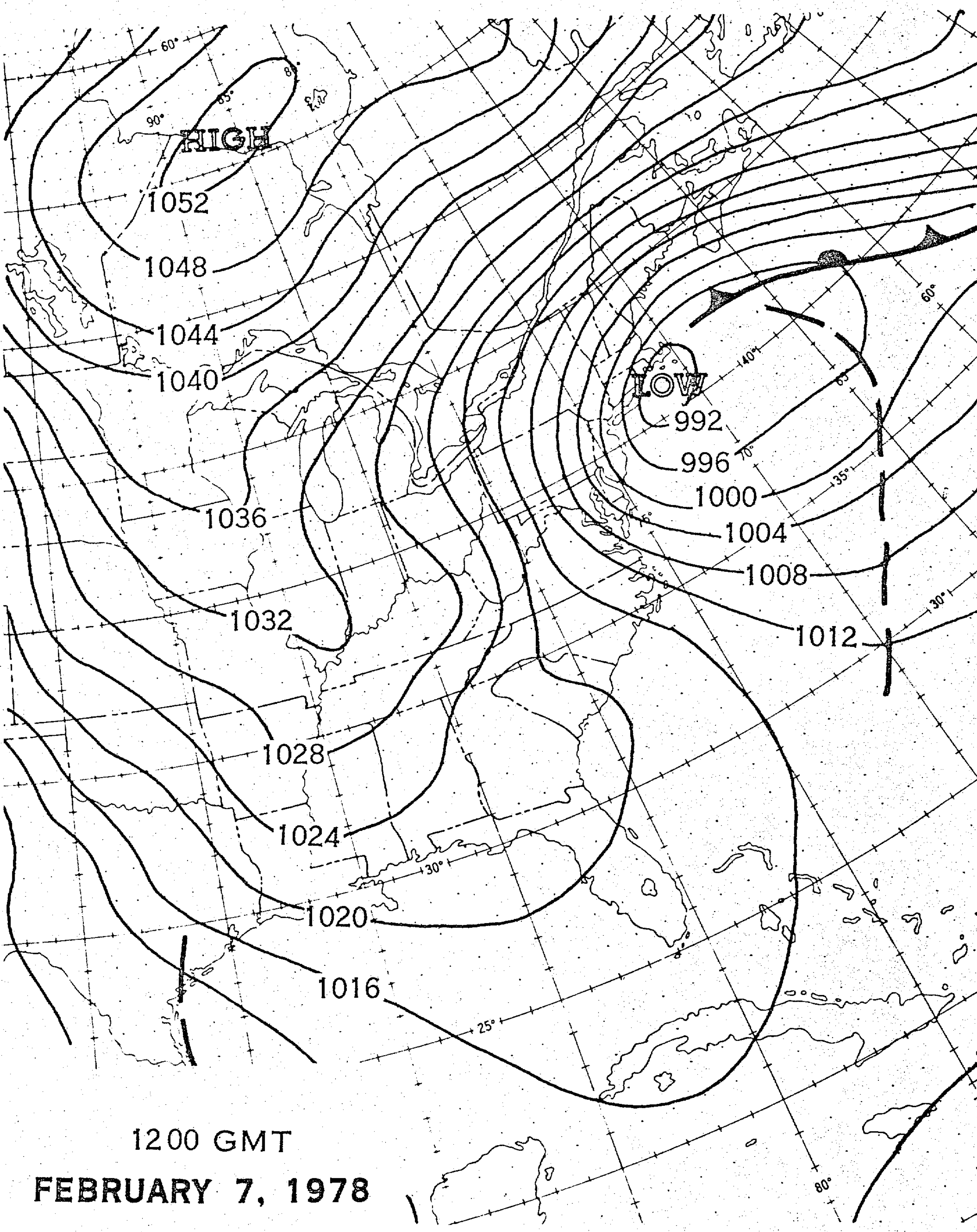

HIGH
1052
1048
1044
1040
1036
1032
1028
1024
1020
1016
LOW
992
996
1000
1004
1008
1012
1200 GMT
FEBRUARY 7, 1978

Fig. 4

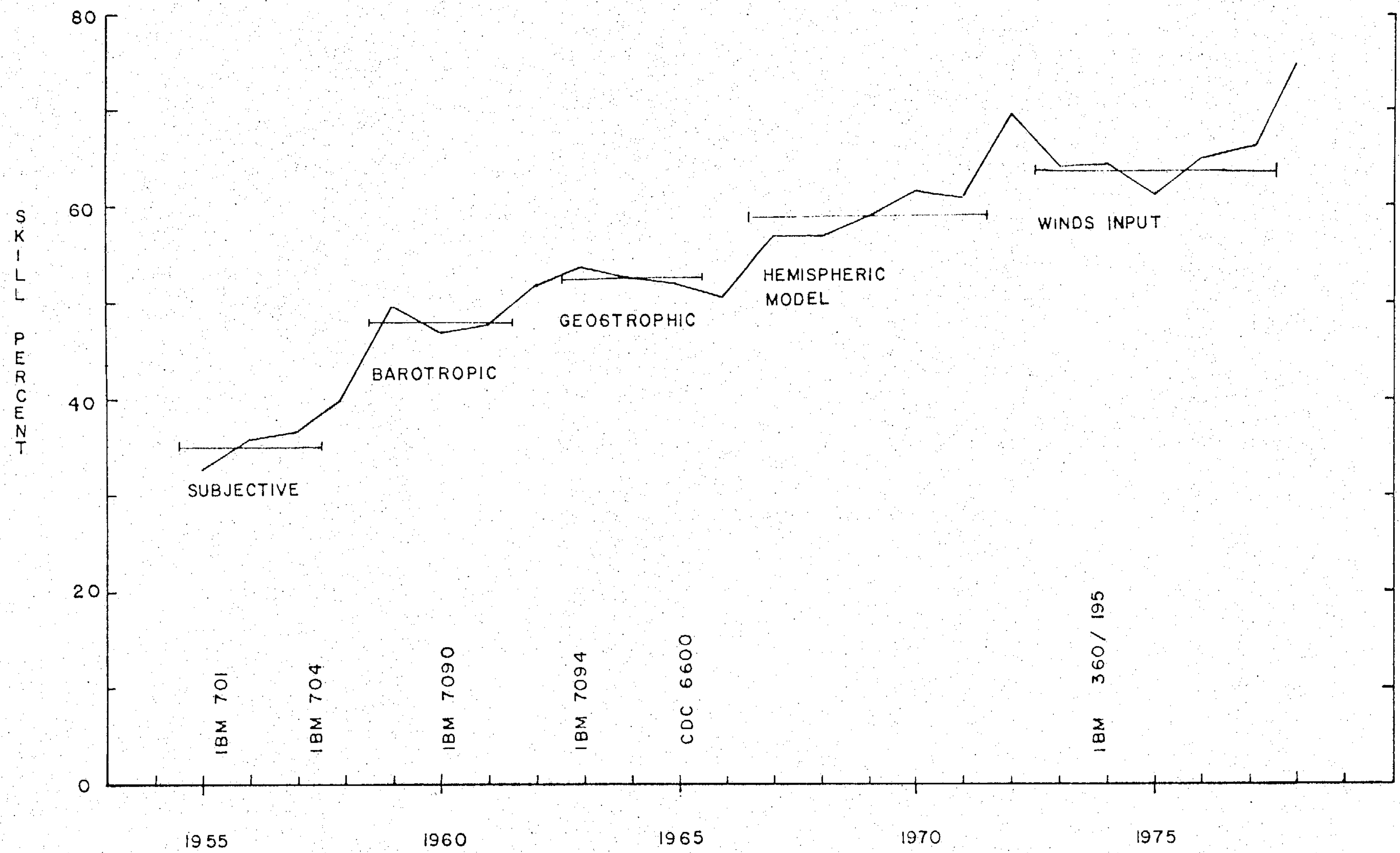
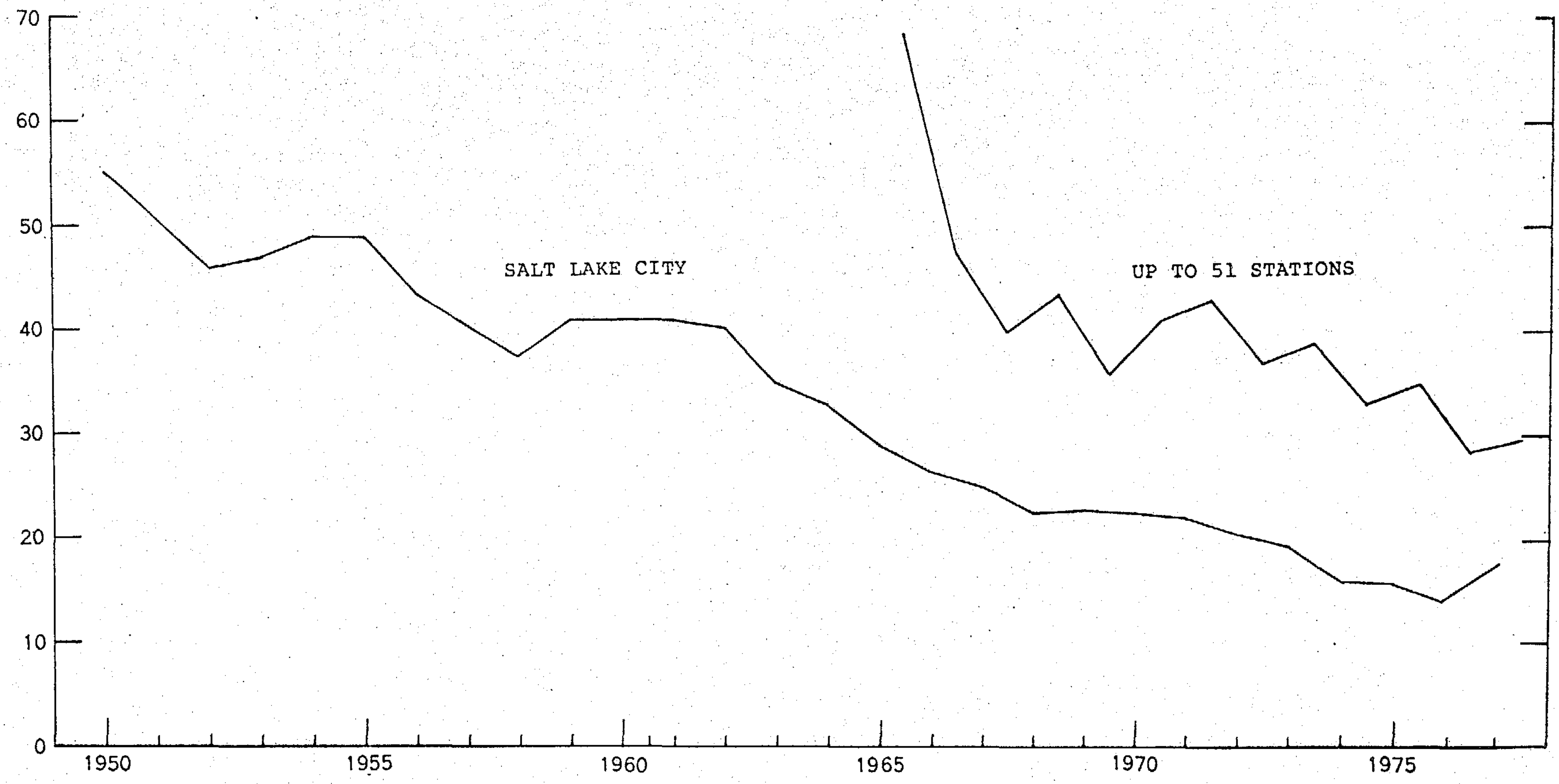

80
60
40
20
0
SKILL PERCENT
SUBJECTIVE
BAROTROPIC
GEOSTROPHIC
HEMISPHERIC MODEL
WINDS INPUT
IBM 701
IBM 704
IBM 7090
IBM 7094
CDC 6600
IBM 360/195
1955
1960
1965
1970
1975

Fig. 5



70
60
50
40
30
20
10
0
SALT LAKE CITY
UP TO 51 STATIONS
1950
1955
1960
1965
1970
1975

Fig. 6